The Nondestructive Evaluation of High-Temperature Conditioned Concrete in conjunction with Acoustic Emission and X-ray Computed Tomography

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ABSTRACT

Portland Cement Concrete plays a vital part of protecting structural rebars or steels when high-temperature fire incidents occur, that induces loss of evaporate water, dehydration of CH, and deconstruction of C-S-H. The objective of the study was to assess fire-damaged concrete in conjunction with nondestructive evaluation methods of acoustic emission, visual inspections, and X-ray computed tomography. The experimental program was to mix an Ordinary Portland Cement concrete firstly. Concrete cylinders with twenty-day moisture cure were treated in a furnace with 400 and 600℃ for one hour. After temperature is cooled down, the concrete cylinders were brought to air or moisture re-curing for ten days. Due to the incident of the furnace, acoustic emission associated with splitting tensile strength test was not able to continue. Future efforts are planned to resume this unfinished task. However, two proposed tasks were executed and completed, namely visual inspections and voids analysis on segments obtained from X-ray CT facility. Results of visual inspections on cross-sectional and cylindrical length of specimens showed that both aggregates and cement pastes turned to pink or red at 600℃. More surface cracks were generated at 600℃ than that at 400℃. On the other hand, voids analysis indicated that not many cracks were generated and voids were remedied at 400℃. However, a clear tendency was found that remedy by moisture curing may heal up to 2% voids of the concrete cylinder that was previously subject to 600℃ of high temperature conditioning.

Keywords: Ordinary Portland Cement, X-ray Computed Tomography, High-Temperature, Voids

1. INTRODUCTION

Portland Cement Concrete plays a vital part of protecting structural rebars or steels when high-temperature fire incidents occur, that induces the loss of evaporate water, dehydration of Calcium Hydroxide (CH), and deconstruction of Calcium Silicate Hydrate (C-S-H). As such causes considerably reduction in strength and induces interfacial instability, as Metha and Monteiro[1] explained. In terms of microstructural perspectives, moistures start to evaporate or escape from the layers of C-S-H, CH, and part of entringite, when the temperature reaches to 300℃. In addition, the decomposition of CH initiates in about 500℃, while C-S-H deconstructs in about 900℃ inside of the concrete. The mineralogy also affects the microstructural properties of concrete subject to elevated temperature. When carbonate aggregates and lightweight expanded shale are blended into the concrete mixtures, 75% of residual compressive strength occurs when temperature reaches to 650℃; in terms of concrete mixed with siliceous aggregates, the same 75% residual strength of concrete happens when temperature only reaches to 427℃. If temperature keeps raising to 650℃, the residual strength of concrete largely downgrades to 25%. It is the mineral phase transitions in quartz or so-called quartz inversion, namely from (α)- to (β)–quartz generally occurring at 573℃ (1060℉), and the quartz expands inside of the concrete mixture, which eventually decrease the concrete compressive strength. Erin et al.[2] indicated the evaluation of visual inspections on fired-damaged concrete on color and surface cracking that was viable. Generally speaking, the color of concrete gets to gray at 300℃ (550 ℉), pink at 550℃ (1000 ℉), black 800℃ (1450 ℉) and white 950℃ (1740 ℉). The surface and internal cracking also increase along with the rise of the temperature until rupture of concrete.

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Pooh et al.[3] investigated the post-fire-curing effect on strength and durability to normal- and high-strength concrete that were exposed to elevated temperatures up to 800 ℃. The compressive strength, rapid chloride diffusion and mercury intrusion porosimetry were evaluated. It was found that the concrete mixes blended with fly ashes, subject to water-curing, and of higher strength that the recovery effects were much pronounced. In addition, the authors also commented if the elevated temperature can be kept below 600 ℃, it is likely the post-fire concrete can recovery thoroughly because the more C-S-H gel composed in concrete exposed to 600 ℃ than that at 800 ℃. Georgali and Tsakiridis[4] utilized the polarization optical microscopy to assess the field cores of 15-year old fire-damaged concrete on surface color changes and cracks as posed to the post-fire forensic investigations. It was identified that limestone aggregates were mixed. Findings obtained from field cores, including parallel cracking, spalling, and color of concrete, indicated the temperature may exceed 800 ℃; the reduction of compressive strength of field cores implied that has reached to 70% implies that temperature exposure may exceed 700 ℃; in terms of microscopic and petrographic observations at the surface near to the fire origin showed carbonate aggregates transformation to Calcium Oxide also demonstrates the temperature may reach to 900 ℃; however, the absence of microscopically visible glassy layer melted from aggregates and cement pastes expressed the possibility that temperature at the surface did not exceed 1000 ℃. Ingham[5] examined concrete mixtures blended with Limestone, Sandstone, Marble, and Granite with 250, 300, 400, 600, 800 and 1000-℃ and discovered that the assessment of fire damage by visual inspection of surface color changes and cracks is practical.

Nondestructive evaluation (NDE) method in conjunction with X-ray Computed Tomography (CT) was engaged to evaluate the fire-damaged concrete by Fukuda et al.[6] and Henry et al.[7]. Both teams utilized sophisticated micro-focus industrial X-ray CT with high resolution—24 and 22 micron respectively to study the concrete microstructural properties in three different conditions, namely before, and after elevated temperatures, as well as being recovered differently by moisture or air-curing. The visual inspections on the virtually-sliced segments both showed the disconnection (or recovery) of the continuous crack and the eliminations of cracks around the interfaces between aggregates and pastes. This research team conducted a pilot study[8] earlier and employed the medical X-ray CT facility with speedy yet rather lower resolution (625 micron) in analyzing the fire-damaged (400 ℃) reactive power concrete (RPC) quantitatively, it was found feasible to perform the quantitate analysis on internal voids distribution of segments.

2. EXPERIMENTAL PROGRAM

In this phase of research work, the objective aimed to employ the medical X-ray CT facility and other NDE methodologies to evaluate fire-damaged Ordinary Portland Cement concrete subject to elevated temperatures. The research scope was to design the OPC concrete mix and cast concrete cylinders, treat 28-day moist-cure cylinders subjected 400 and 600-℃ of elevated temperatures, employ either air or moist-cured of the recovery procedures, and perform NDE methods, including voids analysis conducted by X-ray CT and acoustic emission (AE) coupling with splitting tensile strength test, and visual inspections. It has to be noted that overall concrete mixing, casting and testing tasks were executed at the Civil Materials Laboratory at the Department of Civil Engineering of National Kaohsiung University of Applied Sciences, while the assessment of X-ray CT was conducted at the E-Da/I-Shou University Hospital.

2.1 Materials

One OPC concrete mix (w/c=0.45) were mixed and concrete cylinders were cast. Coarse aggregates and river sands were obtained from local contractors near Kaohsiung, Taiwan. It has to be noted that composition of coarse aggregate was previously identified as the siliceous aggregate. Several trial mixes were made to ensure the appropriate workability that the ratio of total fine and total aggregates by volume was found 41%. Both air entraining agent and superplasticizer were added to warrant the workability without altering the fresh and harden concrete properties. Table 1 presents the mix proportion of OPC in this study. Concrete cylinders with 100 mm (4 inches) in diameters were cast and de-molded after 24 hours. A twenty-eight days of moist-curing process was employed to every OPC concrete specimens to ensure the maturity of concrete mixture.

Table 1. Mix proportions of OPC concrete mixture

OPC	W/C	Water (kg/m^3)	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air Entraining Agent (g)	Superplasticizer (g)
	0.45	159.75	355.0	1115.63	808.63	28.35	453.60

2.2 Concrete cylinders subject to elevated temperatures and visual inspections

After curing process, OPC concrete cylinders were brought to a furnace which is capable of heating up to 900 ℃. The initial plan was to wipe out the existing water out of the cylinders and put cylinders immediately to the furnace for elevated temperature treatment. The initial plan for elevating temperature was set-up by the rate of 10 ℃/minute. However, the first high-temperature conditioning was a failure and cylinder was exploded and shattered everywhere inside of the chamber of the furnace, shown in Figure 1. The high-temperature conditioning later was revised to leave specimens in the ambient room temperature (approximately 20 to 23-℃ and 50 to 70-% in humidity) for one week firstly and later heat up by a lower elevating rate by 3 ℃/minute, which came to a success to treat concrete cylinders up to 400 and 600-℃. When the furnace reaches to 400 and 600-℃, the furnace sustains for one hour. After the high-temperature conditioning and cool down process, visual inspections were explicitly executed on the full as well as the sliced cross-section concrete cylinders to identify the surface color changes and cracks. The “fire-damaged” concrete specimens were later brought to a recovery process, either air or moist-curing for another ten days. It has to be noted that the loss of shattered concrete cylinders resulted insufficient concrete specimens for the proposed task of conducting the acoustic emission coupling with splitting tensile strength test. Another supplementary OPC concrete mixing, casting, and curing job has undergone and acoustic emission associated with splitting tensile testing will be conducted in the next phase of the research.

Figure 1. Shattered OPC concrete cylinder with broken protective steel meshes in the furnace (Photo taken by Dr. Yu-Min Su)

2.3 Nondestructive evaluation by the medical X-ray CT facility

The nondestructive evaluation through the medical X-ray CT was conducted at the E-Da/I-Shou University Hospital. The Somatom® Emotion manufactured by the Siemens Healthcare is a 16-channel X-ray CT facility and provides maximum 0.75 mm in resolution in Z-axis. Figures 2 presents the X-ray CT facility, the focus of the concrete cylinder, and the orientation of the virtual segments. While performing the X-ray CT scan, the concrete cylinder was placed on the patient’s table. The operator positioned the table properly and started the scan. The concrete cylinder was going back and forth through the ring of the facility along with the Z-axis and the embedded sixteen X-ray channels/sources acquired multiple X-ray digital images to construct the three-dimensional reconstruction momentarily. The setting of acquiring the concrete cylinder CT images was to use 110kV with automatic current (mA/μA). Previously NDE research work[8] conducted have identified and adopted setting with the same voltage and automatic current during to scan PCC or asphalt concrete without any problem. After the segments acquired from the facility, series of segments in the medical formatting of DIACOM were brought back to KUAS to proceed the image processing and analysis. It has to be noted that the image processing and analysis were conducted by Mathworks MATLAB R2015b and the ImageJ provided by National Institutes of Health. The goal was to quantitatively evaluate the voids area and ratio of each segments and then conduct a topdown and in-depth voids distribution along the Z-axis. X-ray CT scan was employed to concrete cylinders at "before" and "after" high-temperature conditioning as well as after ten-day of the recovery process. Ultimately, it was to distinguish various voids distributions and determine whether or not the "fire/high-temperature" cause the changes of internal voids and the recovery process heal the voids/cracks.

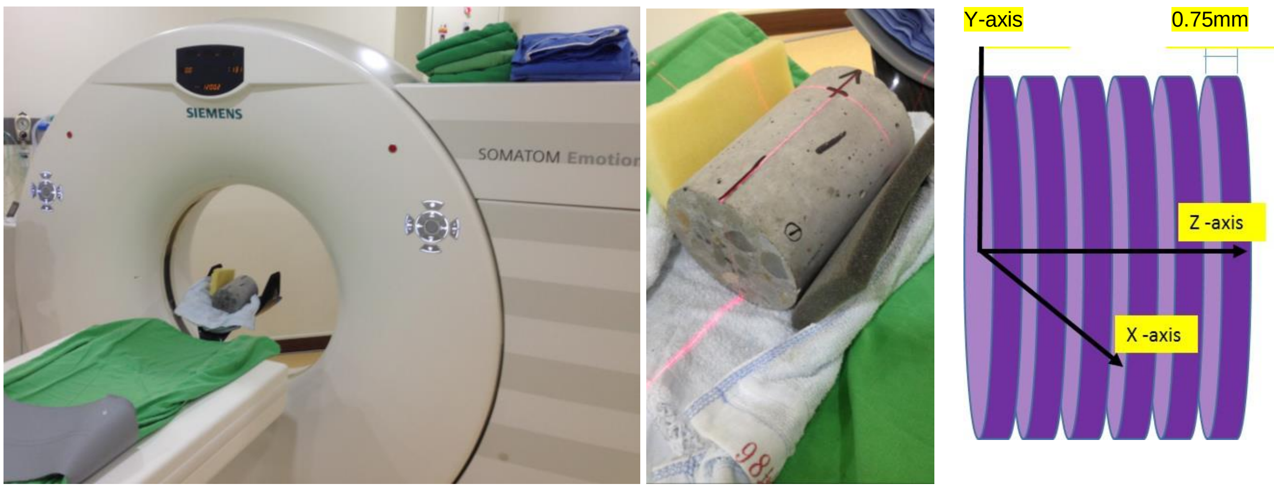
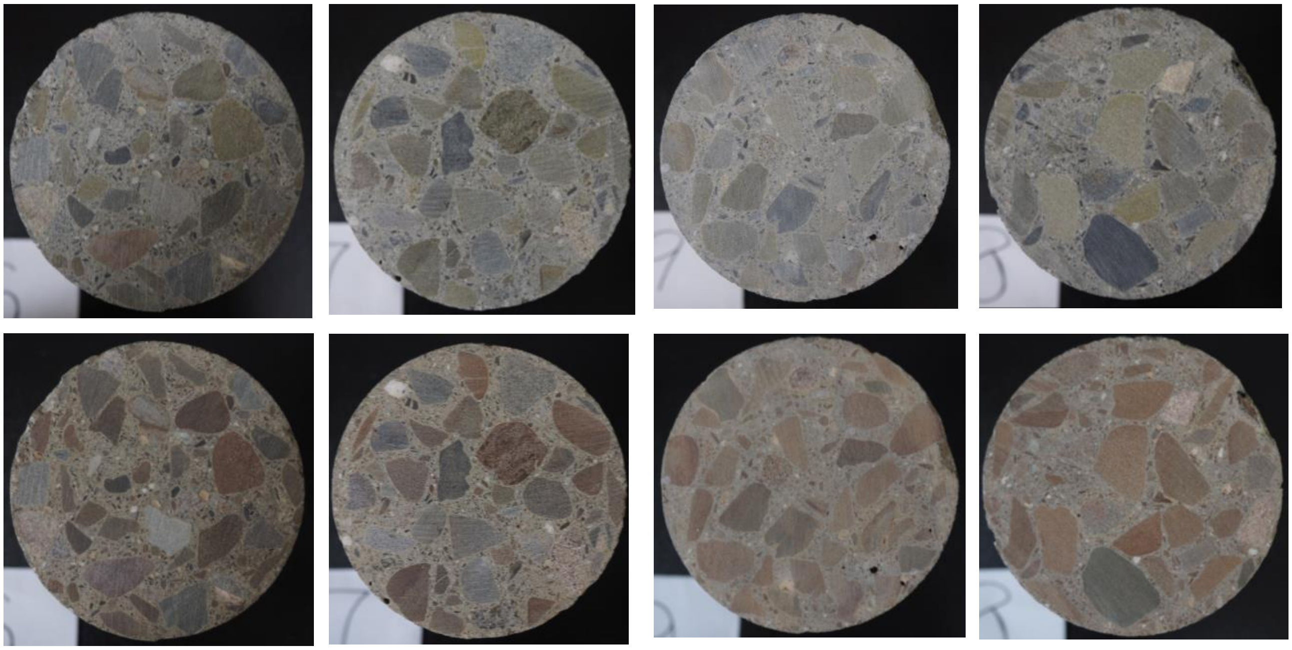


Figure 2. X-ray CT facility, the focus of the concrete cylinder while inserting for nondestructive CT scanning, and the orientation of the virtual segments (Photos taken by Dr. Yu-Min Su)

3. ANALYSIS OF VISUAL INSPECTIONS

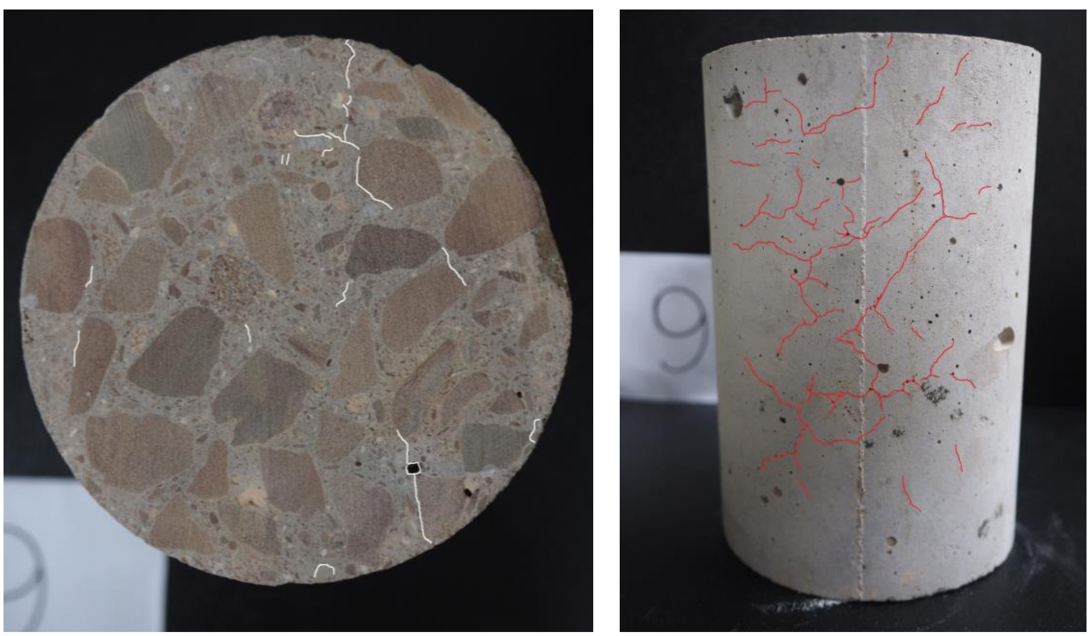
Four concrete cylinders with 28-day moist cure were brought to suffer high-temperature conditioning—two for 400 ℃ and the other two for 600 ℃ and each was performed individually with the visual inspections on the full and cross section of the specimen. Every images were taken indoor by the Olympus E-PL series digital camera and its setting, including shutter speed (1/50), aperture (f=4.0), and ISO (ISO=800), were consistent. Figures 3 (A) and (B) present the cylinders subject to 400℃ with air and moist-curing, respectively; while Figures 3 (C) and (D) demonstrate the cylinders subject to 600℃ with air and moist-curing, respectively. The upper cross-sectional images were taken before the cylinders were brought to high-temperature conditioning, and the colors were similar in aggregates and cement paste; while lower cross-sectional images were taken after the cylinders were subject to high-temperature conditioning, and the ways of color changes were departed. For 400℃, it was found that the siliceous aggregates gradually turned to pink or red, while the cement pastes remain more and less the same color; for 600℃, aggregates and cement pastes transformed much further in pink or red.

In terms of identifying surface cracks, cylinders were conditioning at 400℃ not resulting obvious surface cracks on both cross-sectional and cylindrical length surfaces. However, cylinders were conditioning at 600℃ that occurred quite obvious cracks in cement paste, interfaces between cement paste and aggregates, and extensive spider-web cracks on the cylindrical length surface, shown in Figure 4 (A) and (B), respectively.



(A) (B) (C) (D)

Figure 3. Concrete cylinders subject to (A) 400℃ with air-curing; (B) 400℃ with moist-curing; (C) 600℃ with air-curing (D) 600℃ with moist-curing (Photos taken by Mr. Gwan-Ying Chen)



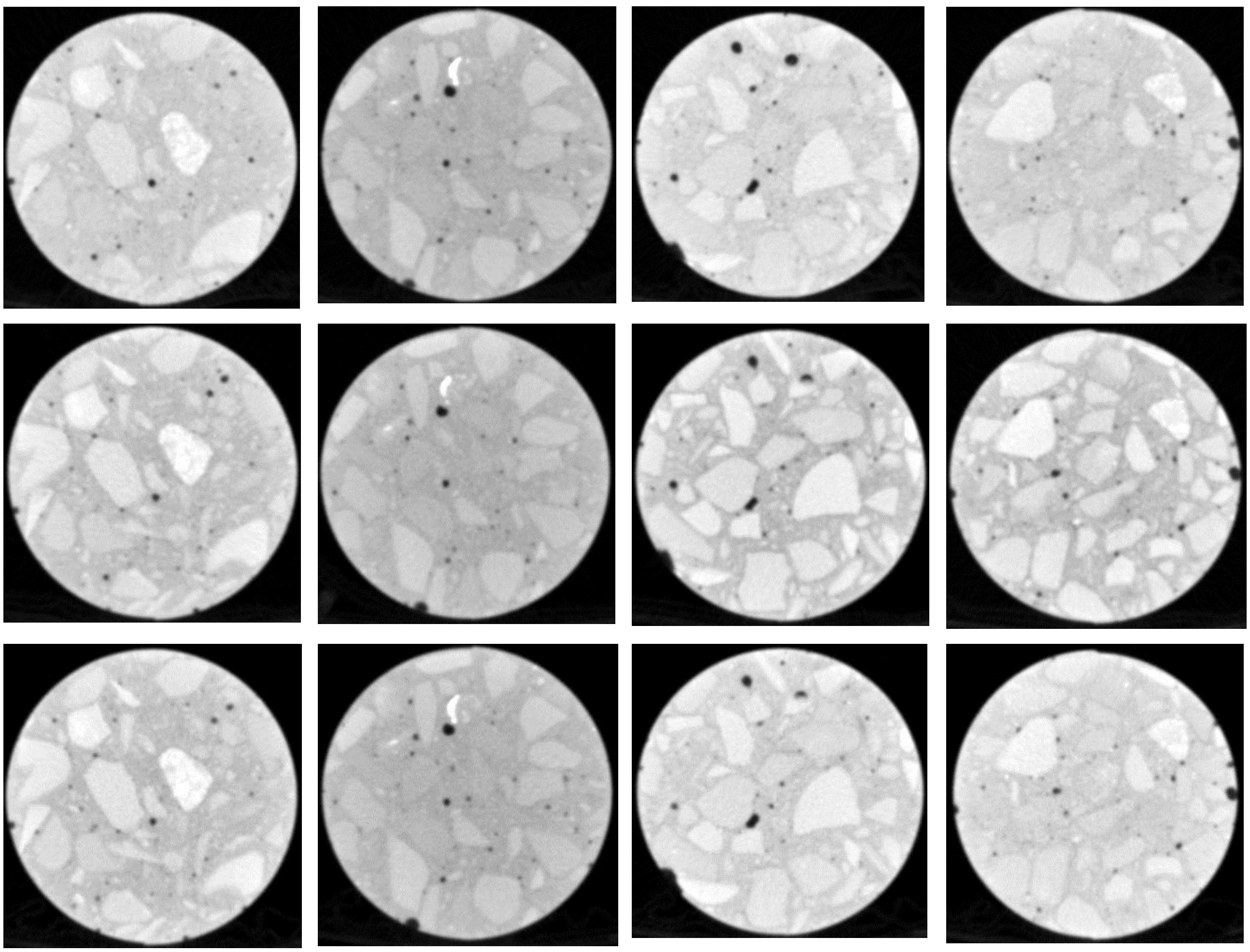
(A) (B)

Figure 4. Concrete cylinder subject to 600℃ (A) Cross-sectional surface cracks (While lines); (B) Spider-web cylindrical surface cracks (Red lines) (Photos taken and modified by Mr. Gwan-Ying Chen)

4. VOIDS ANALYSIS IN CONJUNCTION WITH X-RAY CT FACILITY

4.1 X-ray CT segments visually inspected

Figure 5 showed X-ray CT segments with three different conditions, before (upper) and after (middle) high-temperature conditioning as well as after the recovery (lower) process for four different concrete cylinders—(A) 400 ℃ with air-curing; (B) 400 ℃ with moist-curing; (C) 600 ℃ with air-curing (D) 600 ℃ with moist-curing. Visual inspections were done on each set of three CT segments. It has to be noted although each X-ray CT scan was performed exactly on the same penetration level, namely 110kV and automatic current, the vibrations occurred on the cylinders while moving the patient's table back and forth through the ring that may cause image blurred. The authors have already made the best efforts to perform NDE in conjunction with the X-ray CT. In general, the subtle changes of voids on following segments are not easy to be identified by the visual inspections in Figure 5. It might not viable either to go over every single CT segments and reveal the trivial variations of voids. A rather rationalized approach has to be explored.



(A) (B) (C) (D)

Figure 5. Concrete cylinders subject to (A) 400℃ with air-curing; (B) 400℃ with moist-curing; (C) 600℃ with air-curing (D) 600℃ with moist-curing (X-ray CT Segments taken by E-Da/I-Shou University Hospital and modified by Dr. Yu-Min Su)

4.2 Quantitative analysis with X-ray CT segments performed

A quantitative analysis in voids distribution conducted with Mathworks MATLAB were established to calculate the estimated voids area and used that to estimate the ratio of the voids in comparison with the overall cross-sectional area of each segment. Figure 6 (A)&(B) showed voids estimated versus topdown depth of the concrete cylinders subject to 400℃ with either air or moisture-curing and Figure 7(A)&(B) plotted voids estimated versus topdown depth of the concrete cylinders subject to 400℃ with either air or moisture-curing

Figure 6 (A) indicated that the voids of concrete subject to 400℃ increased only a few, while the following recovery process with air-curing did not remedy the voids much; Figure 6(B) showed a similar tendency in the lower part of the specimen that the recovery process did not help much. However the upper part of specimen indicated otherwise that the moisture curing did help remedy voids significantly. Figure 7 (A) indicated that the voids of concrete subject to 600℃ increased not much but larger than that of 400℃, while the following recovery process with air-curing did not remedy the voids much either; however, Figure 7(B) showed a clear tendency of moisture curing largely help reduce voids. In many segments, it filled (or healed) up to 2% of voids

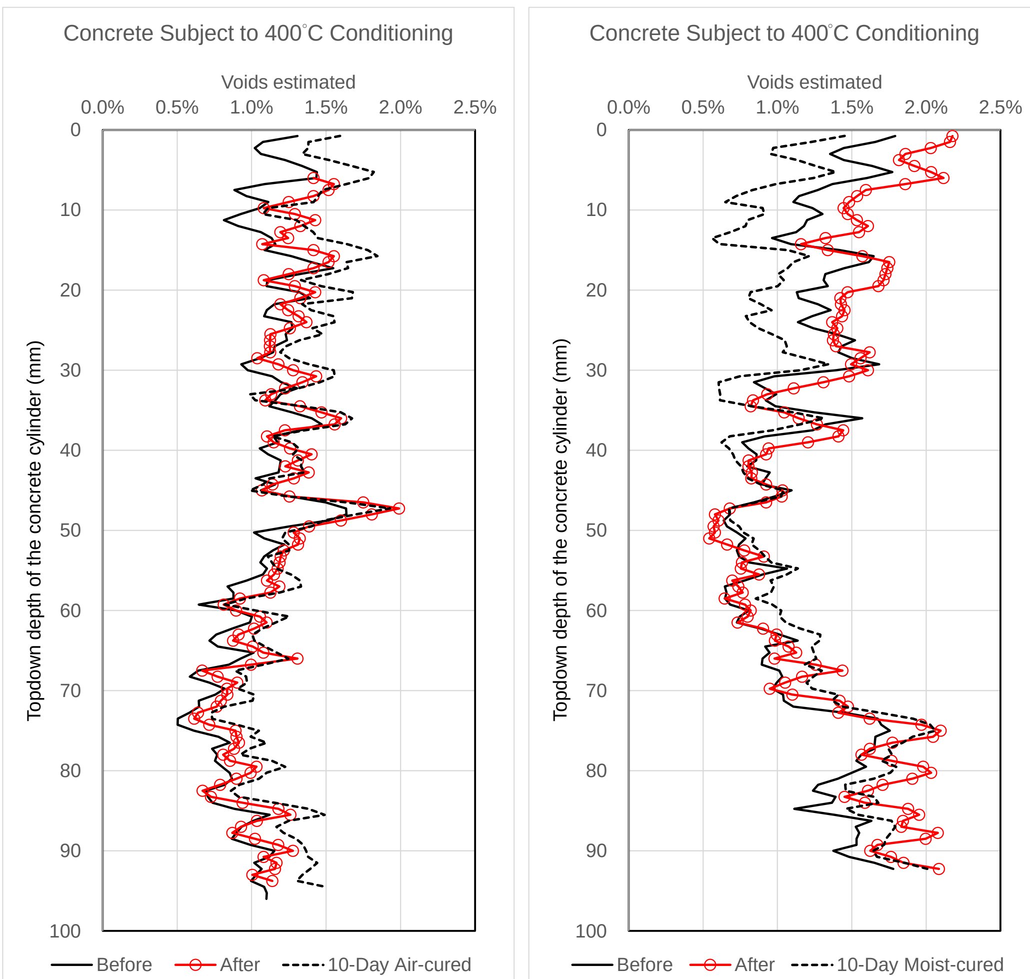
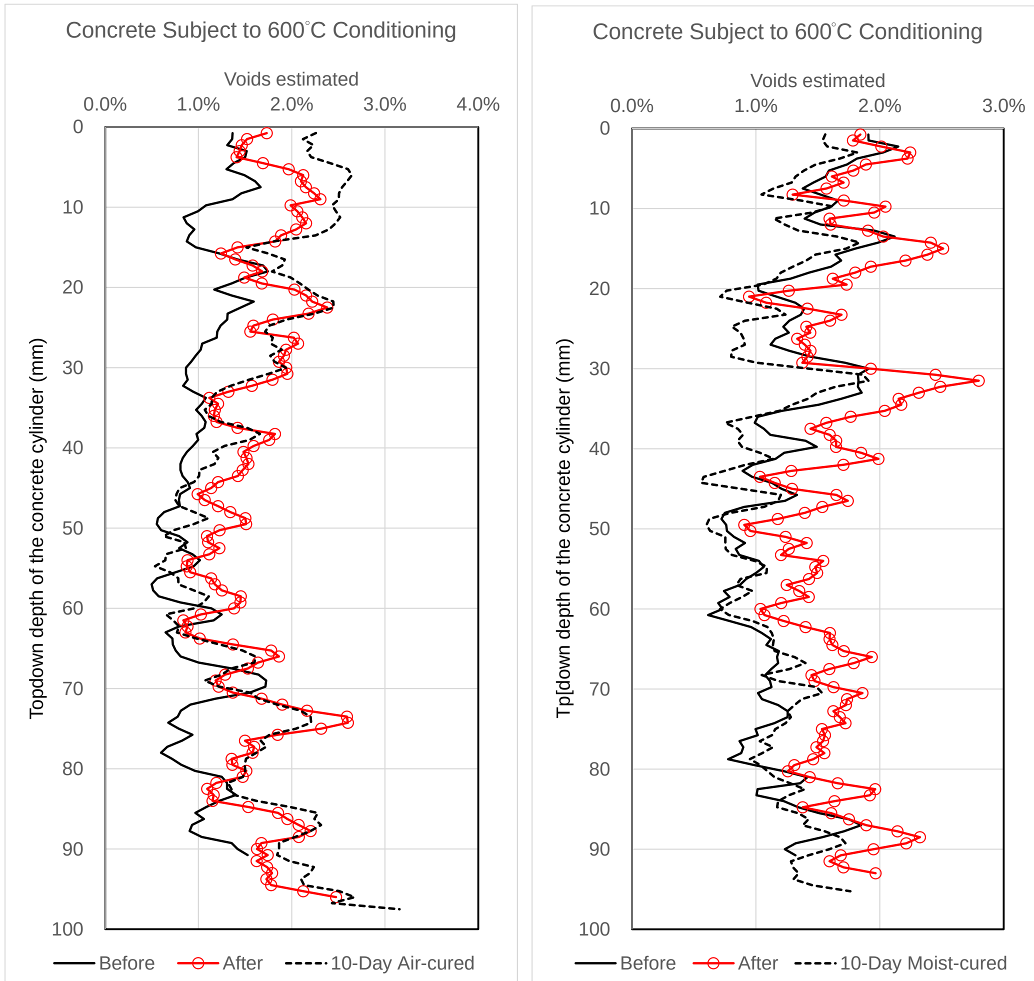


Figure 6. Quantitative voids distribution of concrete cylinders subject to (A) 400℃ with air-curing; (B) 400℃ with moist-curing; (modified by Dr. Yu-Min Su)



(A) (B)

Figure 7. Quantitative voids distribution of concrete cylinders subject to (A) 600℃ with air-curing; (B) 600℃ with moist-curing; (modified by Dr. Yu-Min Su)

5. CONCLUSIONS

The main findings of this phase of research on the use of X-ray CT on fire-damaged OPC concrete are as follows:

• In terms of visual inspections on concrete cylinders subject to 400 and 600-℃ conditioning, part of siliceous aggregates turned to pink or red at 400℃ and almost everything including cement paste transformed colors at 600℃.

• In terms of visual inspections on concrete cylinders subject to 400 and 600-℃ conditioning, no much surface cracks on the cross-sectional and cylindrical length was located at 400℃, but they were radically occurred at 600℃.

•In terms of visual inspections on X-ray CT segments of concrete cylinders subject to 400 and 600-℃ conditioning, it might not easy to observe the subtle changes on segments. A rationalized approach of analyzing segments quantitatively was suggested.

•A quantitative voids distribution approach was established to plot voids distribution versus topdown depth of concrete cylinder with Mathwork MATLAB. Based on the results of voids distribution, not many voids were generated due to the 400℃ conditioning, nor significant changes in voids. However, much more voids were appeared due to the 600℃ conditioning, and more voids were healed. In many segments, up to 2% of voids were remedied.

• Due to the cylinders exploded and shattered in the chamber of the furnace, it was unable to complete the task proposed to utilize acoustic emission with the splitting tensile test. New concrete mix has proportioned and this unfinished task can be added to next phase of the research work.

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